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Particle Size Distribution of E-Cigarette Aeroso ls in Indoor Air

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Abstract: Particle Size distribution of inhalable aerosols is the most significant factor to estimate the aerosol deposition yield at various respiratory tract. Recently, electronic cigarette (EC), as the alternative of tobacco cigarette, is increasingly popular all over the world. However, emissions from ECs may contribute to both indoor and outdoor air pollution. Also, the number of users is increasing rapidly. In this investigation a mainstream aerosol generated from electronic cigarette were characterized in terms of particle number concentrations and size distributions by using diffusion aerosol spectrometer (DAS). Diffusion aerosol spectrometer is used to determine the ultrafine and fine particles emission in the range from 10^{-3}µm to 10 µm. In this work, aerosol number concentration that injected from the electronic cigarette nearly around40k particles/cm3.Most of these particle concentrations within the ultra-fine particles (UFP) size range (0 to 0.2µm) and the other in the size range from 0.3 to 1 µm. The surface and mass size distributions are calculated and presented. The strength of the electronic cigarette is equal $26x10^{11}$(particle/min).

Keywords: Electronic cigarette (EC), size distribution, count distribution, mass distribution, UFP.

1 Introduction

One of the most important factor affecting human health is the exposure to aerosol particles, especially fine (0.1-1 µm) and ultrafine (<0.1 µm) airborne particles [1-7].Because of their larger diffusion coefficient, ultrafine particles have a higher probability than larger particles to penetrate and deposit deeper into the respiratory system.

In general, fine and ultrafine particles are generating usually in indoors with different human activities. Therefore, indoor aerosol particles sources are generally classified according to the occupant's activities. For example, walking generates substantial amounts of aerosol particles larger than 1 µm that are possibly re-suspended from indoor surfaces [8,9].Fine aerosol particles are generated with substantial amounts during cooking, sauna heating, and fireplace [10-17].Smoking is another major source of fine aerosol particles [11,16,18-22]. It was also reported that candle burning generates aerosol particles with range 0.03-3 µm[23,24]. Also, air freshener sprays produce aerosol particles with substantial amounts [16]. Vacuum cleaners operating with or without dust bags may also produce aerosol particles [25-27]. In recent years, electronic cigarettes (e-cigarettes) show a rapidly growing market share and are advertised as a healthier alternative to conventional smoking. The use of e-cigarettes has become increasingly prevalent and as well as being one of the fastest ways to increase the concentration of indoor aerosol particles [7]. The most recent studies indicate to the peak concentrations are more important for health effects than long-term concentration averages [28]. So, reliable measurements of the particle size distribution of the produced aerosol by e-cigarettes are an important physical property for the assessment of respiratory dosimetry but unfortunately have not been heretofore available. Few studies investigated health effects due to the e-cigarette use [29-33]. A review of 16 studies found that e-cigarettes comparable in toxicity to nicotine replacement therapies (NRT) but less harmful than tobacco cigarettes [34]. Nonetheless, there are still some questions about the safety of the chemicals in e-cigarette.

The insufficiency of information on particle size distributions for e-cigarettes is due not only to their novelty, but also as a result of technical hurdles to the measurement of particle size in a high number concentration aerosols containing volatile particulate material. Because of the particle size distribution measurements provide a starting point for respiratory deposition calculations [35], the objective of the present study is to describe a methodology for the measurement of the different particle size distributions and number concentration of e-cigarette

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aerosols in indoor air as a first step of respiratory deposition of e-cigarette aerosols.

2 Experimental Work

The experiments were carried out in the radiation Laboratory in Ural federal university, the volume of this room 65 m^3. Temperature and relative humidity values are varied from23to25^{0}C andfrom40 to 45 %, respectively. Using one of the most used e-cigarettes in the world, Pons, a burning time of approximately 10 min. The puffs were performed by a puffing machine. Main stream aerosols generated from this e-cigarette were characterized.

The laboratory experiments affirmed good accuracy of the Diffusion Aerosol Spectrometer, DAS, on the sizing and the aerosol concentration measurements [36]. So DAS is used for measuring the mainstream aerosol concentration and the number size distribution of nano-particles to submicron size.

2.1 E-cigarettes Design

The E-cigarettes contain a small battery-driven heating unit that vaporizes mixture of chemicals, the so-called “liquids”. They usually contain flavors and carrier substances and may be purchased with and without nicotine. The nicotine content roughly differs between 0 and 20 mg/ml depending on the brand [37]. E-cigarettes are generally designed to resemble traditional cigarettes in dimensions and, to some extent, graphic design. The common components for most e-cigarettes include an aerosol generator, a flow sensor, a battery and a solution (or e-liquid) storage area (see figure 1).

2.2 Technical Description of Diffusion Aerosol Spectrometer (DAS2702-M)

The aerosol diffusion spectrometer can be used to measure the aerosol concentrations and the particle size spectrum, covering a range of sizes from 5 to 200 nm, with the possibility of expanding the upper range to 10 μm. Also, the total concentration and particle size distribution in this range, the air temperature, humidity and atmosphericpressure are measured also. Limit of measured concentrations 100 k particle/cm3. All parameters of the aerosol system and the air environment are output to the monitor and change every 1-2 minutes, more detailed in presented table 1.

The main module of the DAS (2702-M) includes:

- Block of diffusion batteries for measuring the particle size spectrum;

- The particle aggregator to the optically active size;

- Laser aerosol spectrometer for determination of particle concentration and spectrum of submicron particle sizes, schematic sketch of the Diffusion Aerosol Spectrometer Shown in figure 2.

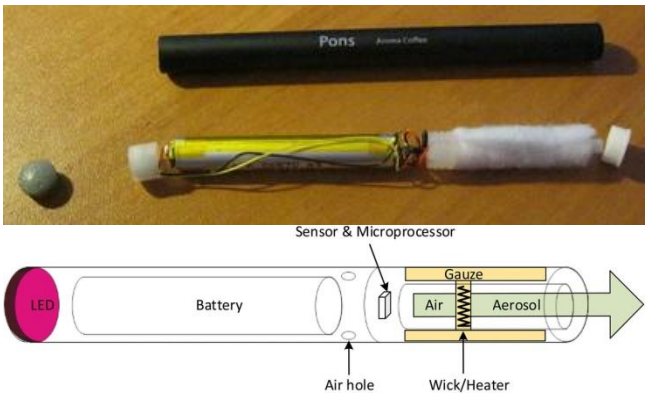

Fig. 1: Typical E-cigarette configuration**.**

Table 1: Characteristics of Diffusion Aerosol Spectrometer (DAS2702-M)

Range of measurement of the sizes of aerosol particles	0.005-0.2 μm (option 0.2-10.0 μm)
Limit of measured concentrations	100,000 particles /cm3
Range of measured relative humidity	5 - 100% (accuracy ± 3%)
Temperature measurement accuracy	± 0.4 ° C
Accuracy of pressure measurement	± 1.5%
Gas flow through sampling tube	2 l / min
Presentation of information	graphic and tabular
Operating system PC	Windows XP
Time of one measurement	1 min.
Continuous measurement time	up to 240 hours
Source of power	AC alternating current 240 V, 50 Hz - DC direct current 12V

The measurement system can be controlled either by a remote keyboard or by a touch panel monitor. The built-in computer controls the operation of the measuring system, processes and stores the measured data both in the processed and in the original form. Results of the measurements are displayed on the monitor screen in graphical and tabular forms. The diffusion aerosol spectrometer DAS with monitoring result is presented in figure 3. The left table shows the concentrations after the corresponding batteries, in the right table concentrations in the corresponding intervals of the sizes. The left graph

represents the histogram of the distribution by size, on the right the change in the total particle concentration with time. In the right column, the relative humidity of the air, the pressure of the atmosphere and the temperature of the surrounding air are given from the top.

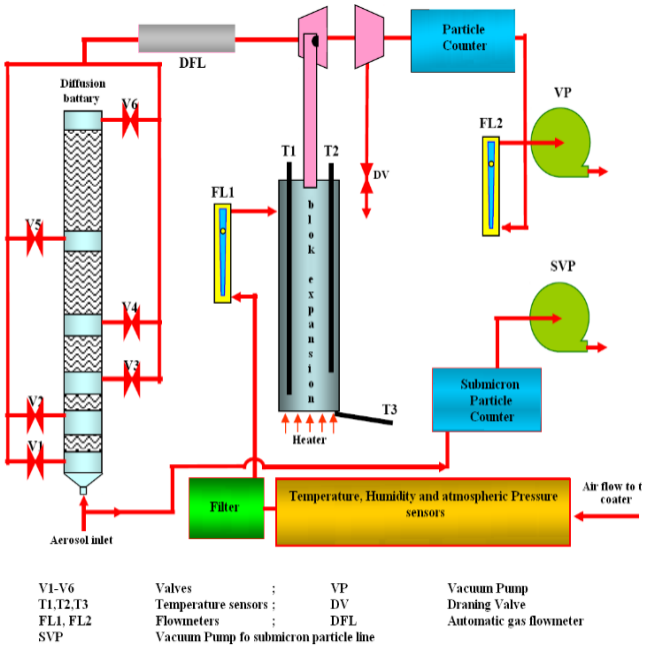

Fig. 2:. A schematic sketch of the Diffusion Aerosol Spectrometer (DAS).

Fig. 3: The Diffusion Aerosol Spectrometer (DAS).

2.3 Size Distribution Functions

Distribution Functions

The mathematical expression selected to describe the aerosol size distribution should be as simple as possible and implies the use of equations with minimum number of parameters which should be selected subject to further evaluation. Distribution by number of particles over the size range will be considered. These are commonly expressed in three ways, dN being the number of the particles in the size range dD_p, D_p is the particle diameter and N is the total number

Aerosol size distributions show modal structure and can be represented by a log normal size distribution function. The lognormal distributions to describe the aerosol population can be given in terms of the number concentration, area, volume distribution and mass distribution. The aerosol log normal number size distribution can be represented as

$$\frac{dN\,(r)}{dlog\,(r)} = \sum\left[\frac{N_i}{\sqrt{2\pi}\,log\,\sigma_i}\right] EXP\left[\frac{-[log(r)-log(r)_{mi}]^2}{2\,log\,\sigma_i^2}\right] \quad (1)$$

wherer_{mi} and σ_i are the mode radius and the standard deviation respectively of the i_{th} mode and Ni its total number density. For a mixture of particles originating from multiple independent sources, the resulting size distribution is a combination of all individual sources. Each component has its specific mode radius, standard deviation (σ) and total number density. The above equation, if summed for i = 1 to 3, represents tri-modal distribution, which will have, three values of N_i, r_{mi} and σ_i. When i varies from1 to 2, the resulting distribution will be bi-modal and when i = 1, it will be a mono-modal size distribution. The log normal distributions to describe the aerosol population can be given in terms of the number concentration, surface distribution or volume distribution. Volume or mass distributions are used to obtain information about the total mass of the aerosol in the air or the mass that is deposited. The surface area S(r) and volume V(r) size distributions are represented as

$$S\,(r) = 4\,\pi\,r^2\left[\frac{dN(r)}{\mathrm{dlog}(r)}\right] \quad (2)$$

$$V\,(r) = \frac{4}{3}\,\pi\,r^3\left[\frac{dN(r)}{dlog(r)}\right] \quad (3)$$

The log normal distributions are best suited to characterize the aerosol components, the aerosol types and their spatial and temporal variability and hence it is widely used for troposphere aerosol studies[38].The corresponding mass and surface area distributions, calculated from the number distribution assuming spherical particles, Equation (2) and(3).

Approximate source strengths, S, of the ultrafine particles using amethod described by Wallace and Ott, [39]:

$$S = \left[\frac{C\,\max * V}{t}\right] \quad (4)$$

where*S* is the source strength or emission rate (particles/min), $C_{max}$is the maximum concentration (cm^{-3}), *V* is the mixing volume(cm^3) and *t* is the time (min) during which a source is on.

3 Results and Discussion

The results of different size distributions (number, surface area and mass distribution) are showed in figure 4. The particle size distributions are presented for back ground (normal lab before the mainstream aerosol particles injected) and after aerosols injection using the e-cigarette at time interval (15, 30, 60, 90 min after aerosol injection). In the back ground measurements, the average aerosols concentration is 6±0.5 k particles/cm3.The particle number and surface distributions have main mode Number Median Diameter (NMD) 89 nm and Surface Median Diameter (SMD) 124 nm respectively with the same Geometric Stander Division (GSD) 1.5. On the other hand, the mass size distribution has a bimodal distribution of aerosols particles is observed with 2mass median diameters (MMD) ~ 120 nm and ~ 2500nm.

Table 2 illustrates the different size distribution parameters. It's clear from the table 2 and figure 4 there are an effects of aging on the different size distributions of aerosols in lab air after aerosol injection. As example, the highest mode at 15 min after injection is 58 nm for NMD and SMD is 104 nm which are smaller than the main mode of the background (89 nm and 124 nm) but the GSD increased from 1.5 to 1.7. The shrinking of the particles number distribution can be attributed to the evaporation of the particles under ideal conditions.

As the time passes from 30 to 90 min as the aerosol concentration decreases directed to background again and the diameters again back to the initial values. As example, at 90 min after aerosol injection the aerosol concentration is 12±1.1 k particles/cm3. The NMD is 83.4 nm and SMD is 116.5 nm with GSD 1.5 and 1.6 respectively. The same satiation occurs for the mass size distribution but with bi-modal distribution. The MMD values are listed in table 2.

Figure 5presents the level of the particles concentrations generated by the electronic cigarette at different sizes from ultrafine (UFP≤ 0.02 µm) to 1 µm. The maximum concentration of UFP was approximately 39 k particles/cm3. The maximum concentrations of particles in the size ranges 0.3, 0.5, 0.7 and 1.0 µm were approximately 550, 515, 173 and 143 particles/cm3 respectively. The 0.7 and 1.0 µm particles concentrations were reached maximum and then decay simultaneously with each other. From the figure also it's observed that the live time of UFP nearly three hours. Unlike other sizes not more one hour for particles size 0.5 µm and only 30 min for 1 µm.

From the presented results, it is much easier to discern modes in the distribution and to obtain a correct impression of the relative number, surface and mass in the different size ranges of the aerosols distribution. The first 20 min after ending smoke will be the most dangerous time as there is a high concentration of all particles especially UFP. Because of, life time of the UFP nearly 3 hwe must be careful when entering places with smokers and make sure of the good ventilation of these places.

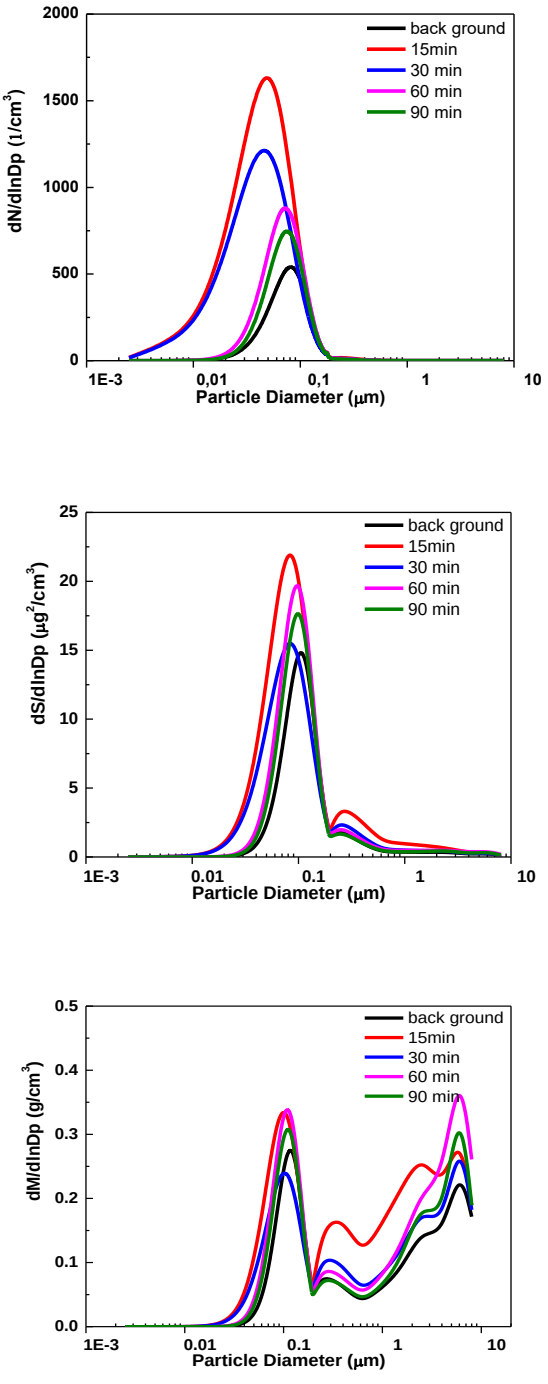

Fig. 4: The number, surface and mass size distribution of the injected aerosol particles.

Table 2: Size distribution parameters Count, surface and Mass median diameter and geometric stander deviation (GSD) of injected aerosol particles from electronic cigarette.

		GSD	SMD	GSD	MMD (fine)	GSD	MMD (Coarse)	GSD
Back ground	89.00	1.5	124.30	1.5	118.86	1.3	2564.45	3.00
15 min	58.16	1.7	104.21	1.7	104.61	1.4	1870.23	3.00
30 min	57.03	1.8	106.65	1.7	106.29	1.5	2303.93	3.10
60 min	80.73	1.5	115.22	1.6	112.77	1.4	2872.39	2.8
90 min	83.41	1.5	116.51	1.6	113.88	1.3	2815.51	2.8

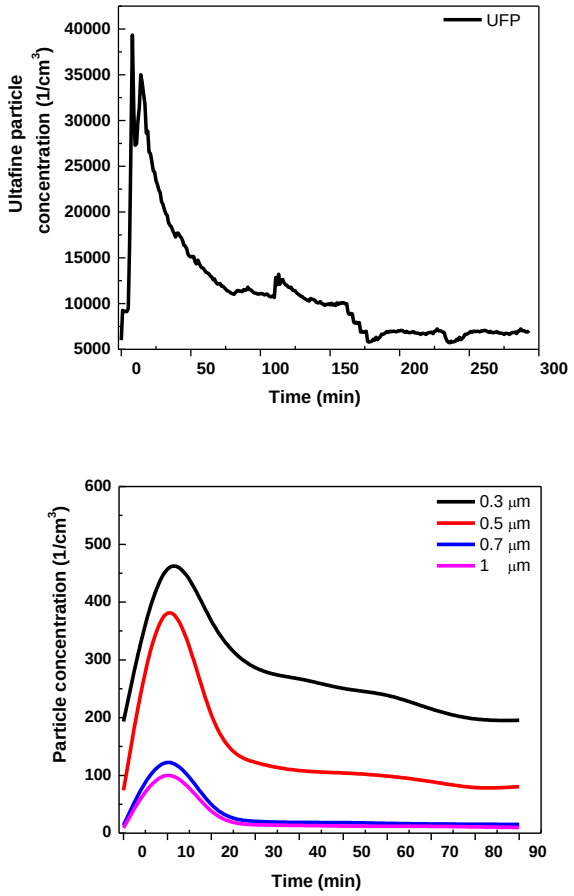

Fig. 5: Aerosol particles concentration of ultrafine function of time by using DAS**.**

4 Conclusions

The concentrations and the size distributions of e-cigarette mainstream smoke were measured with the DAS instrument. The main mode of the aerosol particles from the electronic cigarette is less than 100 nm and the count median diameter ranged from 57 to 83 nm. There was a change in the concentrations and the sizes between different times after injection. Comparing the e-cigarette smoke with that of a conventional cigarette, tobacco smoke, count median diameter was smaller than that of the conventional cigarette, (57-83 nm) against 200 nm. This indicates that some e-cigarettes can deliver considerably more particles into a human respiratory system than conventional cigarettes, even though the e-cigarette smoke contains less harmful constituents. All the particles of the e-cigarette smoke are smaller than 1 μm and some of them are in ultrafine particle range (smaller than 0.2μm), thus able to penetrate deep into a human respiratory system, deposit there and potentially get into the bloodstream. However, these measurements are only a first step in evaluation of possible health outcomes. It is necessary to evaluate a long-term health effect of e-cigarettes

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